Toward a Predictive Model of Arctic Coastal Retreat in a Warming Climate, Beaufort Sea, Alaska

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LONG-TERM GOALS

The long-term goal of this project is to quantify the environmental drivers of extremely rapid coastal erosion in the Arctic, and to begin developing predictive models of future rates of coastal erosion resulting from climate change. Our study is focused on the Beaufort Sea coast within the National Petroleum Reserve – Alaska (NPR-A), approximately halfway between Barrow and Prudhoe Bay. We are focusing our efforts on collecting empirical data that will help us to develop process-based models of coastal change. Toward this end, we are monitoring erosion processes using time-lapse photography, collecting meteorological and oceanographic data from sites along the coast, and archiving climatic and geographic data from the past few decades to identify trends in coastline position through time. We anticipate that our project will help us to predict future patterns of coastal change as a function of projected changes in sea surface temperature, sea ice conditions, and changes in land surface temperatures.

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OBJECTIVES

Our main scientific objective is to understand and quantify the relative roles of thermal and mechanical (wave) energy in driving coastal erosion in the Arctic. We hope that a quantification of these roles through the recent past will help us project rates of coastal erosion into the future as the Arctic climate warms. We are combining high-resolution observations of coastline retreat with meteorological and oceanic monitoring programs. Our planned and completed field data collection includes: 1) measurement of bluff substrate properties including ice content, ice-wedge polygon spacing, and the thermal properties of bluff materials; 2) time-lapse photography to observe coastal erosion processes in real-time; 3) establishment of a meteorological monitoring network to summarize the climatic forcings on the system; and 4) monitoring of offshore conditions including bathymetry, wave fields, and sea surface temperatures. By synthesizing these field observations and remote sensing observations into process-based numerical models, we anticipate that we will be able to predict future patterns of Arctic landscape change in the face of changing climatic

APPROACH

Our technical approach includes direct observation of coastal erosion using time-lapse photography; collection of relevant field data including coastal bluff composition, wave and sea surface temperature records, and meteorological records; and modeling of relevant thermal and mechanical processes.

We have now collected nearly a half a dozen time-lapse photography records from permafrost coastlines. These time-lapse series illustrate the processes driving coastal retreat along sandy and fine-grained oceanic coasts, and along inland lake shorelines. We have collected and analyzed samples of coastal bluff materials to evaluate their behavior when subject to thawing and disintegration. We installed two meteorological stations in the NPR-A to monitor wind speed and direction, air temperatures, solar radiation, and barometric pressure. Combined with existing meteorological stations from the USGS, we now have a detailed timeseries describing the meteorological forcing on the system. We have also deployed wave and temperature sensors offshore, to record incoming mechanical and thermal energy to the coastline. We use remotely-sensed data to reconstruct local decadal time series of sea ice coverage and sea surface temperature. Sea ice concentrations have been analyzed using Nimbus 7-SMMR /SSM/I and DMSP SSMI Passive Microwave data, which runs from 1978 to the present at daily or two-daily time resolution. Finally, we have assembled sea surface temperature (SST) data from the MODIS sensor over the past 8 years showing seasonal and annual variations in SST along the Beaufort Sea coast. Although the relatively low resolution of these data (4 km grid spacing) requires that we treat them as qualitative estimates of the sea surface temperatures along the immediate coastline, this dataset provides us with a view of year-to-year changes in the amount of heat available to drive thermal erosion of coastal materials.

Finally, we have begun developing numerical models describing the thermal and mechanical processes contributing to coastal erosion. Our time-lapse records of coastal position have been used to calculate melt rates, from which we can estimate water temperatures and compare with observations. Models describing the mechanical strength of coastal bluffs can be combined with estimates of melt rate to predict the topple-failures observed in our time-lapse photography. Finally, we are combining offshore records of sea ice position with wind speed and direction to model the delivery of wave energy to the Beaufort Sea coastline.

The personnel involved in these activities are as follows: Analyses of time-lapse photography and meteorological records is being undertaken by Dr. Wobus. Sea ice analyses and wave modeling have been conducted by undergraduate Cori Holmes and Dr. Overeem. Masters student Nora Matell developed thermal models of lake erosion, and compiled remote sensing datasets from the NPR-A. Numerical models and data mining code have been developed by Drs. Anderson, Wobus and Overeem. USGS scientists Clow, Urban and Jones assisted with retrieval of sensors during the 2008 summer season. Wave sensors were built by collaborator Tim Stanton at the Naval Postgraduate School in Monterey, and were deployed during the summer field season in 2009.

WORK COMPLETED

Over the past year, we presented five talks and posters at national meetings and local symposia; we submitted one paper to a peer-reviewed journal; we had two students complete theses (one masters and one undergraduate); and we completed our second full field season. Our field work included servicing of our two meteorological stations; re-measuring coastal position relative to benchmarks established in 2007; and deploying new time-lapse cameras in more sandy coastal environments. We also contracted with a private marine services company to deploy wave sensors equipped with autonomous temperature sensors, to catalog the timeseries of thermal and wave energy through a summer season. These sensors have been retrieved late in September 2009, providing us with a record of approximately 2 months of both wave and temperature data. During the academic year, we also developed computer codes that dramatically improve our ability to process remotely sensed data describing sea ice concentrations and sea surface temperatures relevant to our study area.

Graduate Student Nora Matell completed her Masters in Geological Sciences in April 2009. Her thesis was titled “Coastal erosion and thermal impact of thaw lakes in a warming landscape, Arctic Coastal Plain, Alaska,” and was entirely funded by this project. Nora participated in the summer 2008 field season, helping to deploy two meteorological stations, to document the constitution of the seacliffs near Drew Point, and to install cameras and flags to monitor coastal erosion. In the academic year she performed detailed GIS analysis of existing imagery of the local North Slope landscape, conducted laboratory analysis of samples collected from frozen bluffs along the Beaufort Sea coastline, and constructed a numerical model of the evolution of thaw lakes in this permafrost landscape.

Undergraduate Cordelia (Cori) Holmes completed a senior honors thesis, which was jointly funded by this project and by undergraduate research funds from the University of Colorado. Her thesis was focused on developing algorithms to automate the delineation of the summer sea ice edge in high-resolution (250-m) MODIS satellite imagery. Cori developed a set of Python scripts to locate the sea ice edge in sequential daily MODIS images, create GIS grids and polygons delineating the total sea ice extent, and calculate the fraction of open water in the area immediately offshore from our study site. These algorithms will be applied to MODIS data from other years to evaluate the relationship between the duration and timing of and the rate of coastal erosion.

Last fall we produced a video from our time-lapse photography which was posted on the New York Times “Dot Earth” website. As of this writing, this video has been viewed approximately 28,000 times.

RESULTS

Much of the fiscal year was spent processing field data from our 2008 and 2009 field seasons. In the laboratory, we calculated the ice content of seventeen composite samples collected from bluffs at Drew

Point. Ice contents (by mass) ranged from 25-95%, with most of the samples having ice contents in excess of 50%. Loss on ignition has been completed for four of these samples, and indicate organic contents ranging from approximately 13-35%. These data describing bluff substrate properties are being used to evaluate mass balance of materials lost from the bluffs and into the nearshore zone.

Analysis of erosion data from the summers of 2007 and 2008 indicate that annualized erosion rates were very similar over these two years. Processing of MODIS SST data and analysis of storm energy is ongoing, to determine whether there are substantial differences in either of these datasets.

One of our major goals for FY2009 was to use our time-lapse imagery to quantify the relative roles of warming surface waters and wave energy from storms in driving coastal erosion. Toward this end, we deployed autonomous temperature sensors in the Beaufort Sea immediately offshore from our timelapse camera installations. These sensors were lost due to undermining of the bluffs onto which they were anchored. Lacking detailed Beaufort Sea temperature records to calibrate our models of thermal erosion, we have leveraged a timelapse sequence documenting shoreline erosion along an inland lake where we have simultaneous water temperature measurements. Since wave energy is lacking in this lake environment, this record has allowed us to calibrate a model of purely thermal erosion along a permafrost coastline. Our simple model suggests that previously published models of bluff erosion predict well the observed erosion rates (Figure 1).

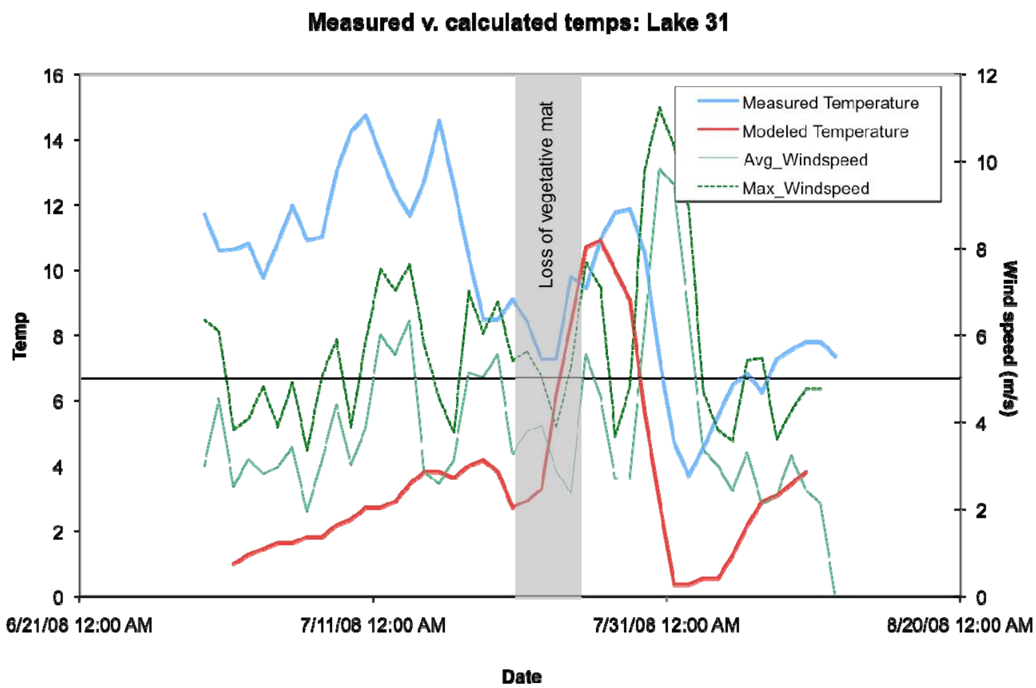

Figure 1: Lake Shore Erosion rate drives modeled temperature over summer of 2009.

The next step is to take these models to the Beaufort Sea coastline. Pending retrieval of our offshore buoys, we currently lack detailed time-series of sea surface temperatures in the shallow sea. However, the rapid retreat of the Beaufort coastline after the last appearance of sea ice – even in the absence of substantial wave energy – strongly implicates a thermal driver for the coastal erosion that we have observed (Figure 2).

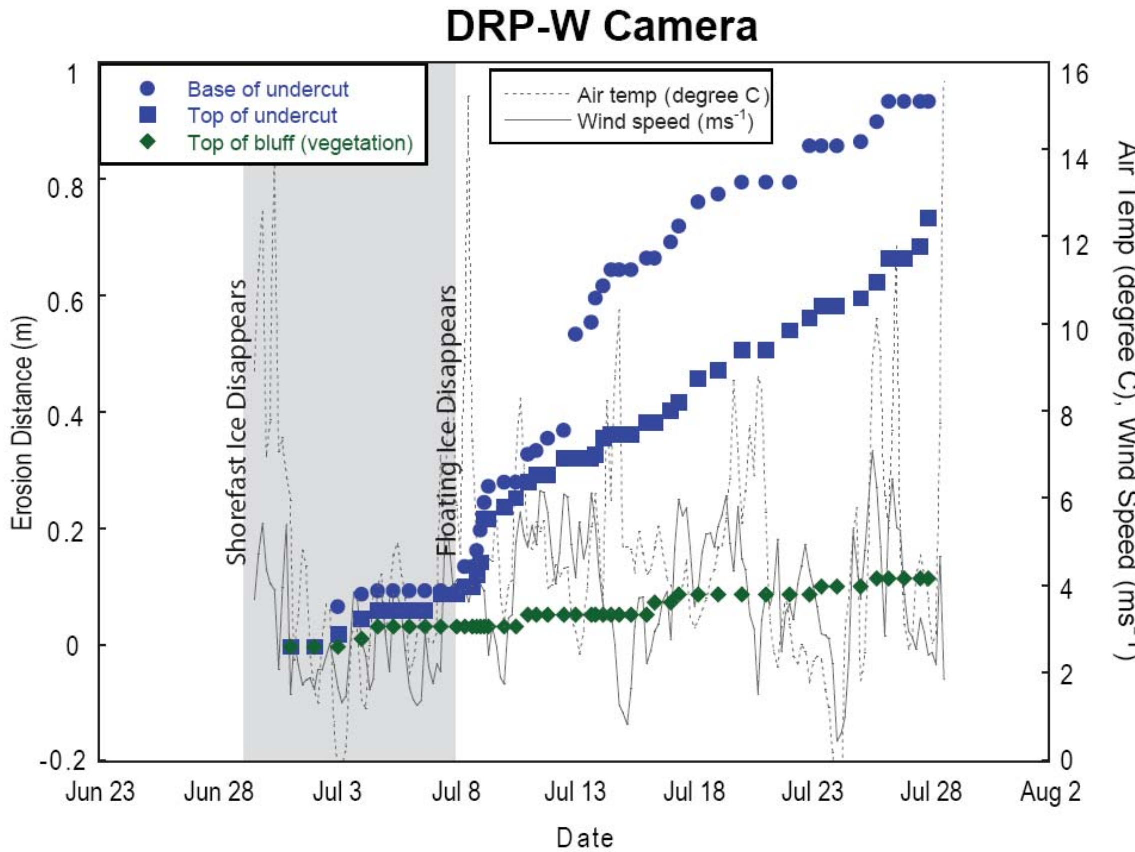

Figure 2: Rate of coastal erosion over July 2008 as reconstructed from time-lapse imagery at Drew Point along the Beaufort Coast, concurrent air temperature and wind speed observed at the in-situ meteorological station shows that erosion is ongoing even in relatively calm ocean conditions.

Thus far, we have used remotely sensed records from the MODIS satellite to reconstruct timeseries of sea surface temperature and to evaluate the total thermal erosion potential in this setting. Comparisons of these coarse-resolution data with observations of coastal erosion rates from repeat measurements of onshore benchmarks also indicate that thermal processes might account for the majority of erosion that we have observed over two summers of monitoring (Figure 3).

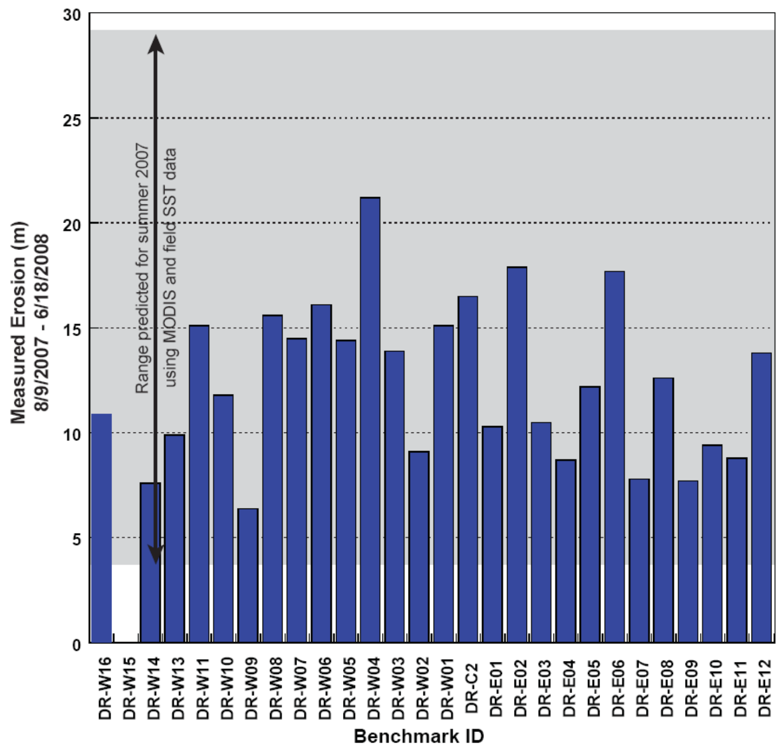

Figure 3: Integrated coastal loss over an entire season (9th of August 2007- 18th of June 2008) as reconstructed from repeat survey transect along Drew Point.

As a first step we used Nimbus 7-SMMR /SSM/I and DMSP SSMI Passive Microwave data to assess sea ice concentration around the Drew Point coast. This dataset runs from 1978 to the present at daily or two-daily time resolution, but has a low spatial resolution (25 by 25km gridcells). We analyzed the data to determine ‘open-water distance’, the distance from a coastal cell towards the sea ice margin where concentration rises above a wave dampening threshold (we used >50% ice). This is allows to show how fetch develops over the year and how it is related to the 20 year average fetch (Figure 4). Analysis of storm records is ongoing to evaluate the role of mechanical (wave) erosion over the same time periods.

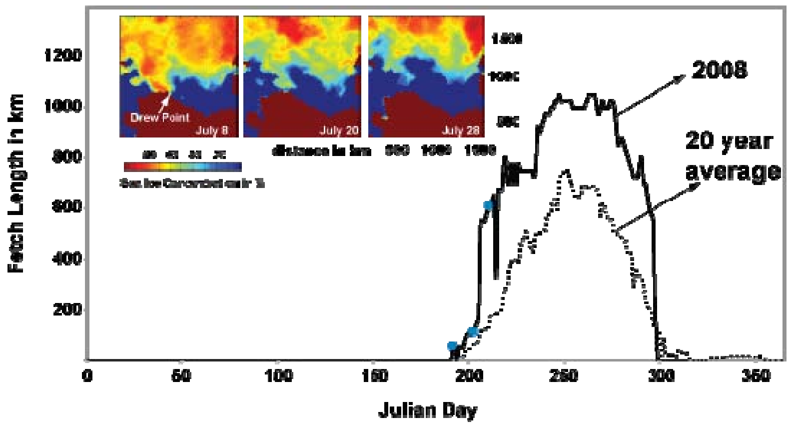

Figure 4: Fetch Length at at Drew Point for different stages over the summer season 2008 is reconstructed from Nimbus-7 Passive microwave data, 2008 has open water distances that are 100's of km longer than the 20 year average conditions.

Our offshore work during the summer of 2009 gave us our first look at the detailed bathymetry in the shallow Beaufort Sea. One hypothesis to be tested is that if coastal erosion rates have in fact accelerated over the past century, there should be an inflection in the bathymetry that reflects this acceleration. There are suggestions from our bathymetric surveys that such an inflection exists in the nearshore environment (Figure 5), which would be consistent with the idea that coastal erosion rates have accelerated in the recent past.

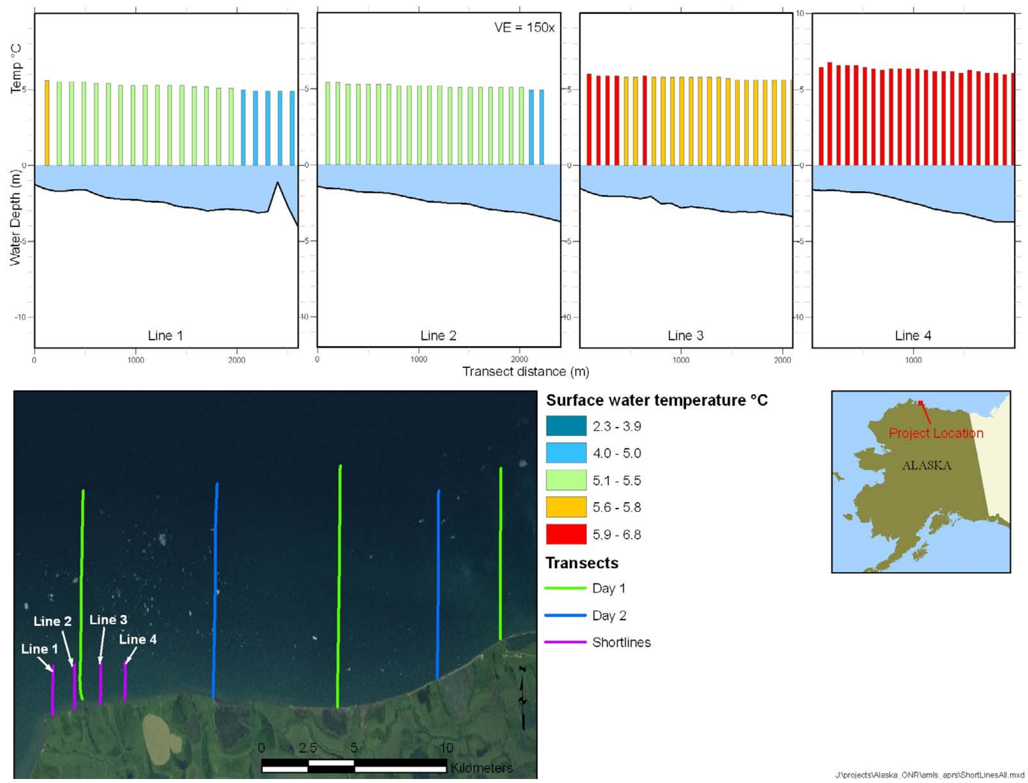

Figure 5: Survey lines of nearshore bathymetry and measured SST temperatures, July 2009.

We also measured sea surface temperatures from the boat to collect a snapshot of sea surface temperatures in the shallow Beaufort Sea. A pair of autonomous temperature sensors deployed in the swash zone over our week in the field also demonstrates both diurnal and secular variations in sea surface temperatures over this short time (Figure 6). Together, these measurements underscore the variability in sea surface temperatures in this environment, both spatially and temporally. Models of thermal energy delivered to the coastline must acknowledge this spatial and temporal variability.

Importantly, we are leveraging our monitoring of oceanic sites with our inland lake site, at Lake 31. At both locations we have recorded both bottom temperatures and near-surface temperatures of the water column. As can be seen in Figure 5, the evolution of the water temperatures in lake site differs greatly from that at the oceanic site, here at Point Lonely. While both sites are in shallow water (order 1 m), the lake site is always warmer than the ocean, and displays a much stronger diurnal signal. In addition, over the period in which the time series overlap, the two records display diverging trends. At Lonely, in the ocean, the water column is always well mixed, there being no discernible difference between bottom and near-surface water temperatures. In contrast, at the Lake 31 site, the water is well mixed most of the time, but stratifies over periods that appear from our met record to correspond to times of low winds speeds. In the next year we will be analyzing these records, as well as thermal records from the moored wave sensors and from another lake site monitored over the last 2 years by the USGS in order to better our understanding of what controls the temperature history of these water masses.

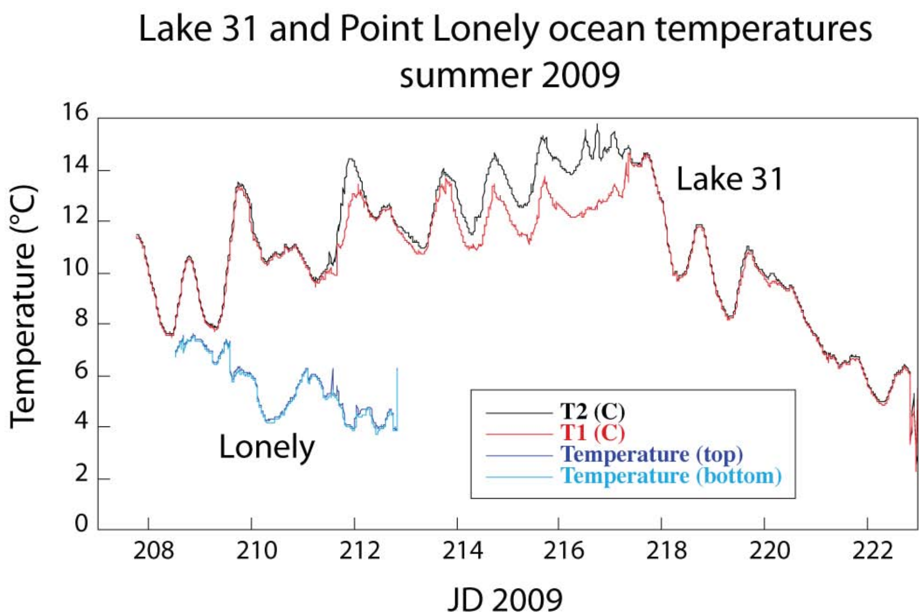

Figure 6: Lake surface temperature time series for sensors in top and bottom of the water columns at Lake 31, as well as a near-coastal SST timeseries in top and bottom of the water columns at Lonely.

IMPACT/APPLICATIONS

Our field data and observations to date validate the hypothesis that both thermal and mechanical energy are driving coastal erosion in the Arctic. These observations underscore the potential for continued very rapid landscape and seascape change in the Arctic: if climate change drives continued increases in sea surface temperatures, coastal erosion rates may continue to increase. In areas where coastal retreat is primarily a thermal problem, our observations might have important implications for our ability to predict future rates and patterns of coastal change. For example, models which predict future changes in sea surface temperatures might provide a simple means of predicting future rates of coastal change in ice-rich environments.

In a much more general way, we have featured early results of this project in presentations to the general public. The movie on ‘Alska’s Eroding Coast’ has been shown at the large plenary closing ceremony of the International Polar Year (IPY) in Geneva, Switzerland. In addition, this case-study featured as an example on ‘Modeling Arctic Coastal Erosion’ in the policy document ‘Arctic Coasts 2009 – a Circumpolar Review’ that will be published by IASC-LOICZ-AMAP.

RELATED PROJECTS

PI Anderson and co-PI Overeem are both members of the Community Surface Dynamics Modeling System (CSDMS) terrestrial working group (http://csdms.colorado.edu/index.html). We anticipate that our project will tap the broader expertise of the CSDMS consortium as we move into the modeling component of our study. Photos and movies of the eroding permafrost coast, as well as thawing lake shores at our field site have been added to the Educational Gallery of the CSDMS: http://csdms.colorado.edu/wiki/index.php/Coastal_GL4

The developed model for 'Lake-Permafrost with Subsidence' developed by graduate student Nora Matell has been added to the Model repository of CSDMS and will thus become available as open-source code for interested earth scientist worldwide.

PIs Wobus and Anderson are both involved in an NSF-sponsored project to understand weathering in alpine environments. Thermal models of ground temperatures as well as technologies developed for monitoring weather conditions, collecting time-lapse photographs, and deploying self-contained temperature probes are creating synergies between these two projects.

PUBLICATIONS

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Peckham, S., Overeem, I., Sediment Transport in a Changing Arctic: River Plumes, Longshore Transport and Coastal Erosion. Arctic Change Meeting, December 10th, 2008. Quebec, Canada.